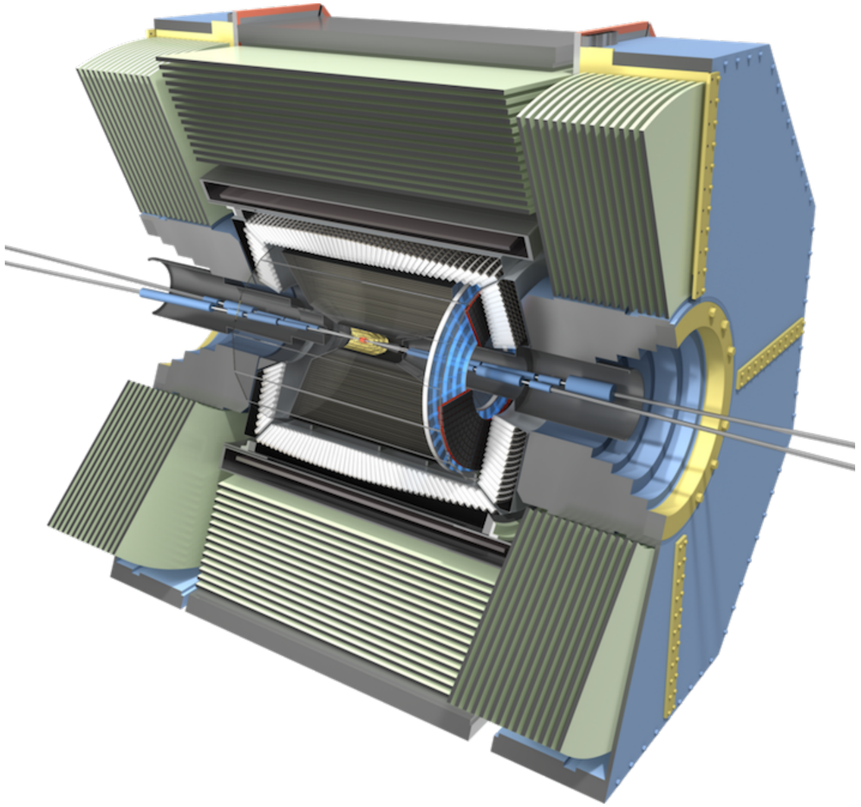
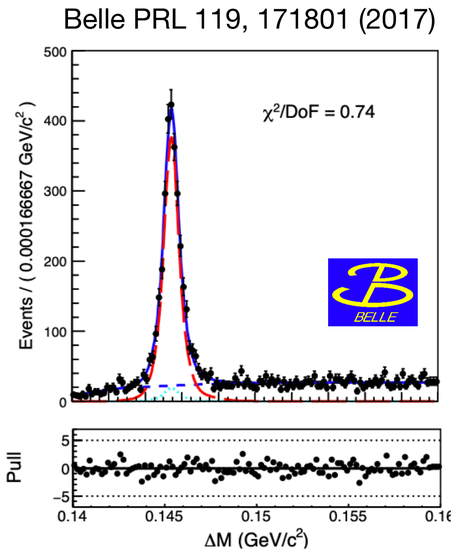


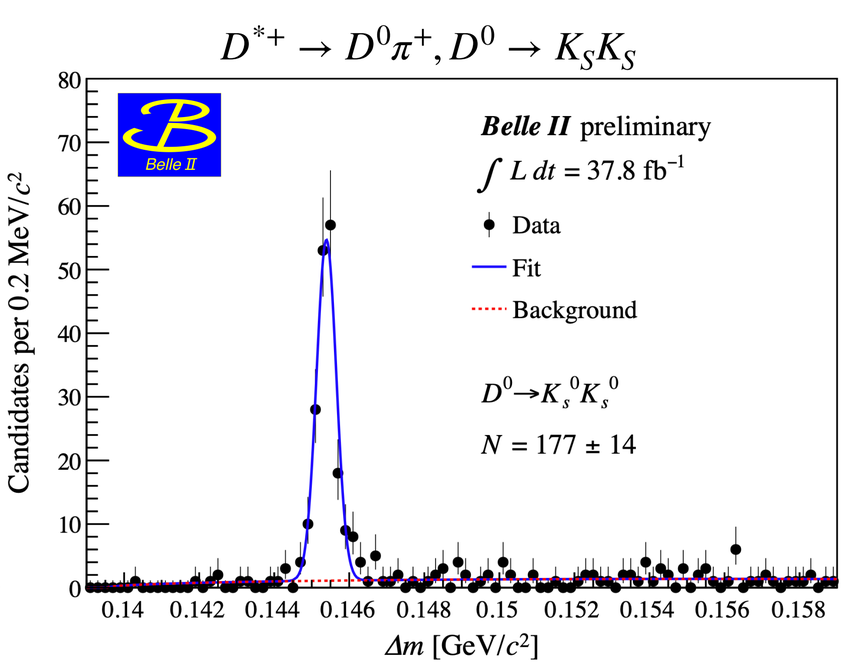
Charm physics at Belle II

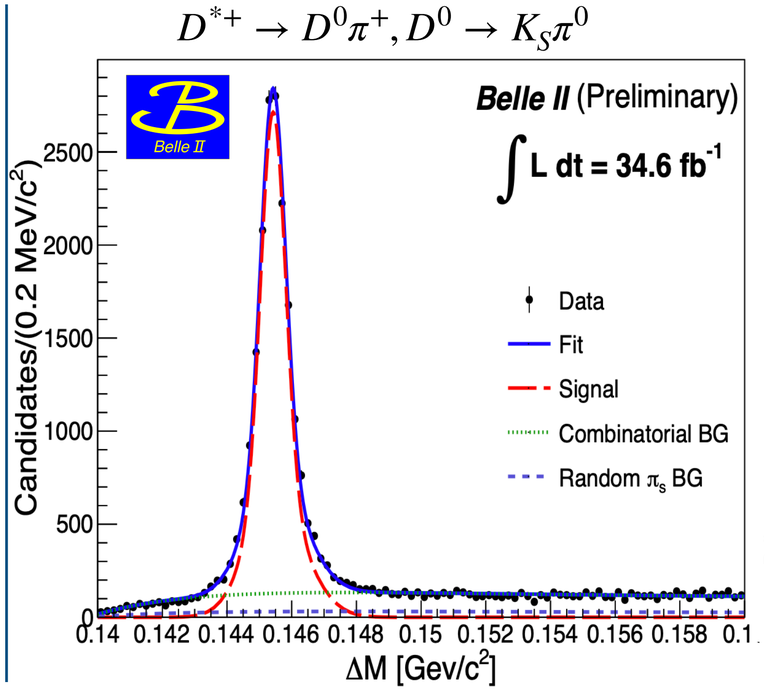
Jake Bennett
University of Mississippi
Snowmass virtual town hall - October 2, 2020

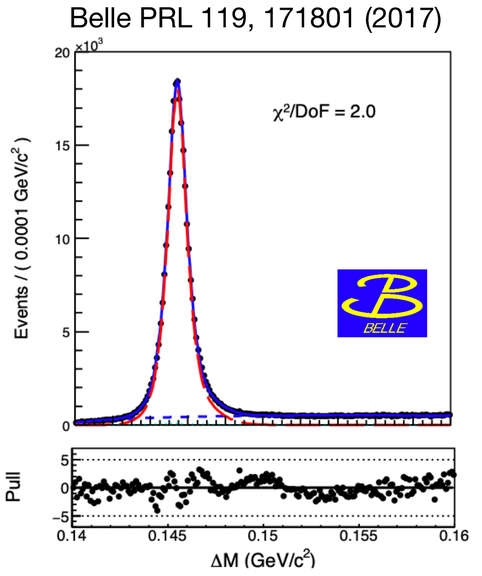
Belle II prospects and status

- Goal: collect 50x the Belle data - tens of billions of charm mesons, baryons
- Belle II can measure, in both neutral and charged final states, branching fractions, CP asymmetries, isospin asymmetries, polarization, etc.
- Since data taking began in 2019, collected ~75 fb^{-1}
  - Useful to study reconstruction performance, resolutions, systematics, etc.
  - Performance approaching that of Belle after just 1.5 years, though there is room for improvements









*qualitative comparisons only

Potential for direct CPV measurements with 50 ab^{-1}

- Comprehensive search for direct CPV, including final states with neutral particles
  - Important to clarify the picture of CPV in the charm sector
- Precision on the order of 10^{-4} with the full Belle II dataset, even for neutral modes
  - Some particularly interesting modes such as $D^+ \to \pi^+\pi^0$, for which CPV in the SM is negligible

Mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K^0_S\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.02
$D^0 \to K^0_S K^0_S$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.23
$D^0 \to K^0_S\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K^0_S\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K^0_S\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.02
$D^+ \to K^0_S K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.04
$D_s^+ \to K^0_S\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K^0_S K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

Belle II Physics Book
Prog. Th. Exp. Phys. 2019, 1232C01 [arXiv 1808.10567]

Search for NP through *T* violation in *D* decays

- Measure non-zero values for a *T*-odd observable to search for *T* violation
  - Complimentary to *CP* violation measurements due to difference strong-phase dependence in the contributing amplitudes
- Four-body *D* decays:

$$C_T = \mathbf{p_1} \cdot (\mathbf{p_2} \times \mathbf{p_3})$$

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}$$

$$\bar{A}_T = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}$$

$$a_{CP}^{T\text{-odd}} = \frac{1}{2}(A_T - \bar{A}_T)$$

Experiment	Decay	Luminosity	$a_{CP}^{T-odd}(\%)$
BaBar (2010)	$D^0 \to K^+K^-\pi^+\pi^-$	470 fb^{-1}	$+0.10 \pm 0.51 \pm 0.44$
BaBar (2011)	$D^+ \to K_sK^+\pi^+\pi^-$	520 fb^{-1}	$-1.20 \pm 1.00 \pm 0.46$
LHCb (2014)	$D^0 \to K^+K^-\pi^+\pi^-$	3 fb^{-1}	$+0.18 \pm 0.29 \pm 0.04$
Belle (2017)	$D^0 \to K_s\pi^+\pi^-\pi^0$	966 fb^{-1}	$-0.028 \pm 0.138^{+0.023}_{-0.076}$
Belle (2019)	$D^0 \to K^+K^-\pi^+\pi^-$	966 fb^{-1}	$+0.52 \pm 0.37 \pm 0.07$

- Belle II can significantly expand on these measurements
  - Statistical and systematic precision
  - Variety of final states, particularly including neutral particles

CP violation in charmed baryon decays at Belle II

- Charmed baryon decays largely unexplored
  - LHCb studied $\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$, ΔA_{CP} = (0.30 ± 0.91 ± 0.61)%
  - Expectations from U-spin symmetry suggest modes of interest

$$A_{CP}(\Lambda_c^+ \to pK^-K^+) + A_{CP}(\Xi_c^+ \to \Sigma^+\pi^-\pi^+) = 0$$
$$A_{CP}(\Lambda_c^+ \to \Sigma^+\pi^-K^+) + A_{CP}(\Xi_c^+ \to pK^-\pi^+) = 0$$
$$A_{CP}(\Lambda_c^+ \to p\pi^-\pi^+) + A_{CP}(\Xi_c^+ \to \Sigma^+K^-K^+) = 0$$

- Some significant benefits to studies at Belle II
  - Neutral final states can be accurately measured (e.g. $\Sigma^+ \to p\pi^0$)
  - e^+e^- collisions allow for better disentanglement of detector and production asymmetries
  - More straightforward to extract CP asymmetries, rather than CP asymmetry differences

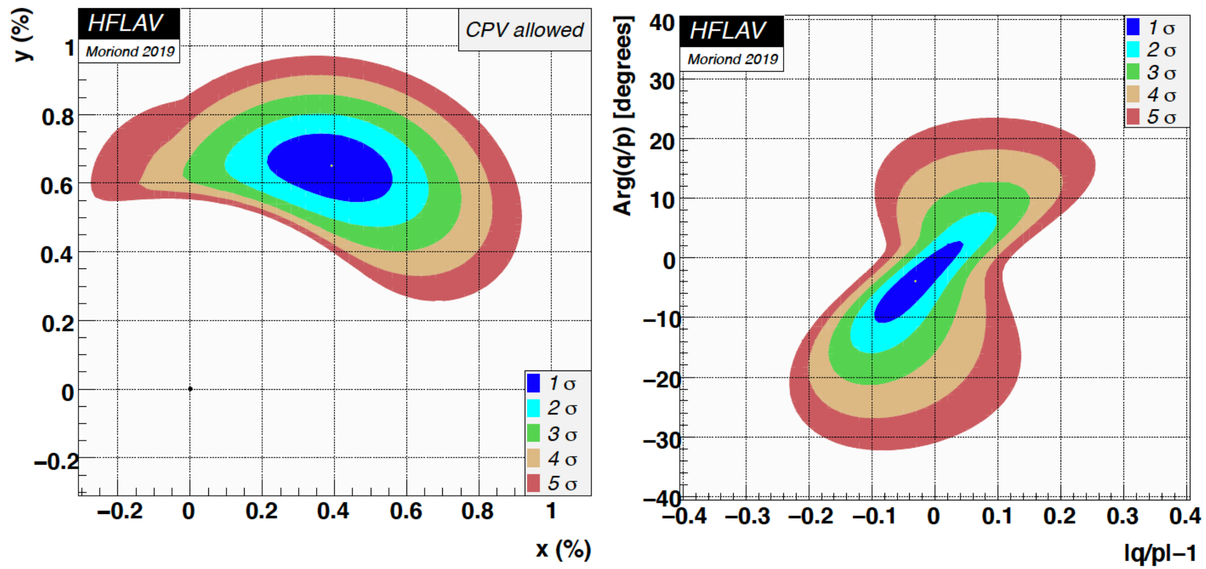
Indirect CPV in charm mixing

- SM mixing rate is sufficiently small that NP contributions may be detectable
- First evidence of $D^0 - \bar{D}^0$ mixing from Belle/BaBar in $D^0 \to K^+K^-, \pi^+\pi^-, K^+\pi^-$
- Mixing measured in several decay modes from Belle, BaBar, CDF, LHCb
- High statistics Belle II data can improve precision with, for example, $D^0 \to K_s\pi^+\pi^-$

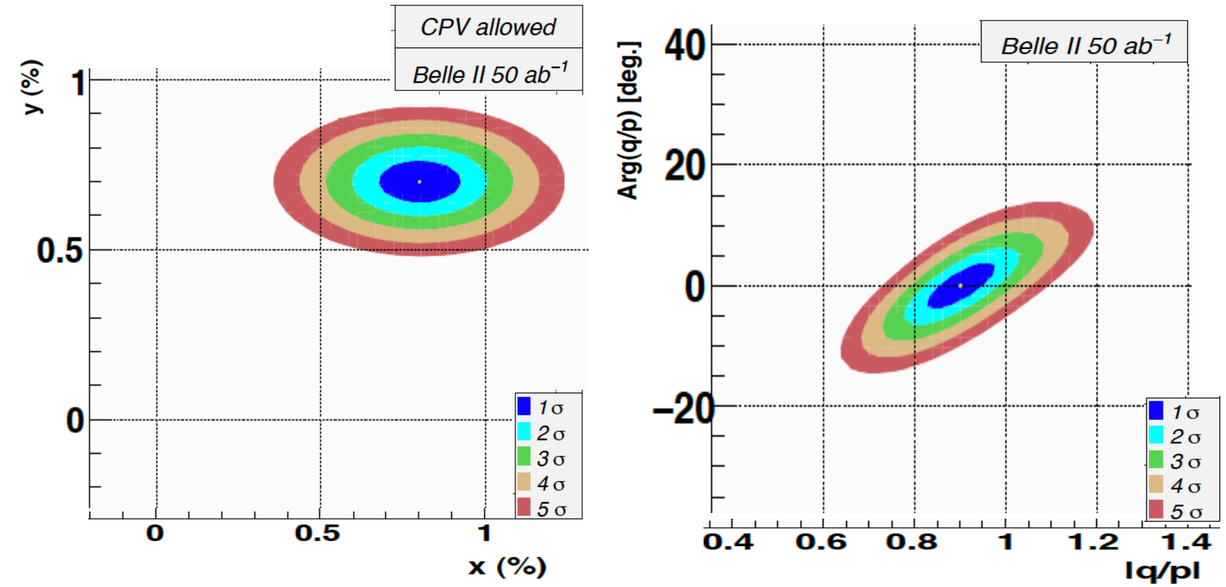
Data	stat.	syst.		Total	stat.	syst.		Total
		red.	irred.			red.	irred.	
	σ_x (10^{-2})				σ_y (10^{-2})			
976 fb^{-1}	0.19	0.06	0.11	0.20	0.15	0.06	0.04	0.16
5 ab^{-1}	0.08	0.03	0.11	0.14	0.06	0.03	0.04	0.08
50 ab^{-1}	0.03	0.01	0.11	0.11	0.02	0.01	0.04	0.05
	$\lvert q/p \rvert$ (10^{-2})				ϕ $(^\circ)$			
976 fb^{-1}	15.5	5.2-5.6	7.0-6.7	17.8	10.7	4.4-4.5	3.8-3.7	12.2
5 ab^{-1}	6.9	2.3-2.5	7.0-6.7	9.9-10.1	4.7	1.9-2.0	3.8-3.7	6.3-6.4
50 ab^{-1}	2.2	0.7-0.8	7.0-6.7	7.0-7.4	1.5	0.6	3.8-3.7	4.0-4.2

Conservative: do not include improvements in decay time resolution, which is a factor of ~2 over Belle/BaBar

Moriond 2019



Belle II @ 50 ab^{-1}

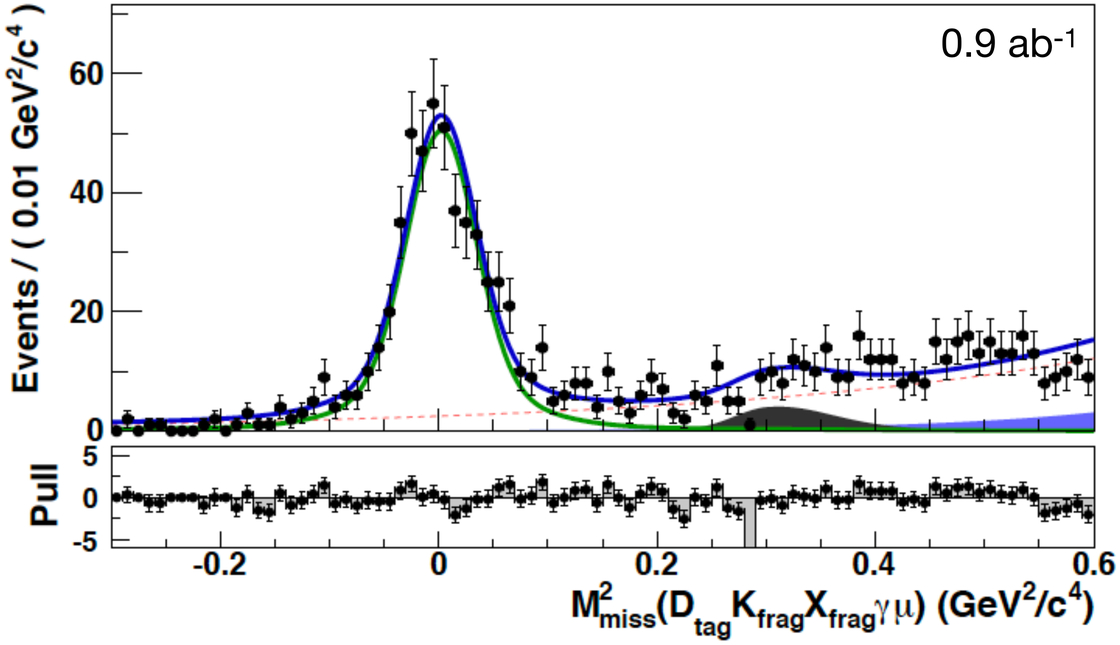


*zoomed to similar scales

Leptonic and semileptonic charm decays

- Goal: precise decay constants and form factors
  - Provides a test for Lattice QCD
  - Input from Lattice QCD to measure CKM elements
- Recoil method successfully exploited for Belle D_s decays
- Belle II statistics allow
  - Measurements of absolute branching fractions
  - Studies of semileptonic decays
  - Searches for rare/forbidden decays with missing energy
- Also works for charmed baryons

Belle: JHEP 1309, 139 (2013)



Channel	Observable	Belle/BaBar Measurement		Scaled	
		$\mathcal{L}$ [ab^{-1}]	Value	5 ab^{-1}	50 ab^{-1}
Leptonic Decays					
$D_s^+ \to \ell^+\nu$	μ^+ events	0.913	492 ± 26	2.7k	27k
	τ^+ events		2217 ± 83	12.1k	121k
	f_{D_s}		2.5%	1.1%	0.34%
$D^+ \to \ell^+\nu$	μ^+ events	-	-	125	1250
	f_D	-	-	6.4%	2.0%

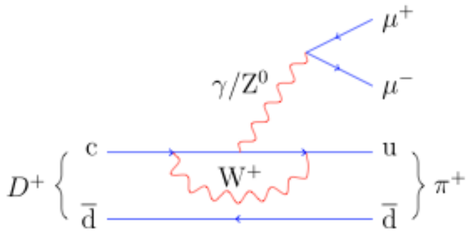
Progress heavily dependent on theoretical side
(LQCD improvements necessary to fully exploit larger data sets)

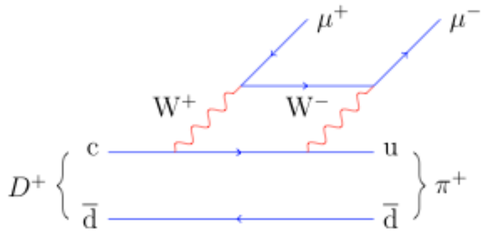
Rare and radiative decays

- NP contributions could enhance CP asymmetry in radiative decays $D^0 \to V\gamma$ by up to an order of magnitude
  - Current measurements statistically limited

			Belle result (~1 ab^{-1})	5 ab^{-1}	50 ab^{-1}
Rare and Radiative Decays					
$D^0 \to \rho^0\gamma$	A_{CP}		$+0.056 \pm 0.152 \pm 0.006$	± 0.07	± 0.02
$D^0 \to \phi\gamma$	A_{CP}	0.943	$-0.094 \pm 0.066 \pm 0.001$	± 0.03	± 0.01
$D^0 \to \overline{K}^{*0}\gamma$	A_{CP}		$-0.003 \pm 0.020 \pm 0.000$	± 0.01	± 0.003

- Rare decays generally mediated by quark-level FCNC transitions $c \to u\ell^+\ell^-$, $c \to u\gamma^*$
- Studies of $c \to u\ell^+\ell^-$, analogous to $b \to s\ell^+\ell^-$ transitions, useful for tests of LFU/LFV
  - Belle II competitive for electron channels





$D^0 \to$	$\mathcal{B}$ measured	Belle expected $\sigma(\mathcal{B})$ or $\mathcal{B}$ UL	Belle II expected $\sigma(\mathcal{B})$ or $\mathcal{B}$	SM SD $\mathcal{B}$	SM LD $\mathcal{B}$
$\pi^+K^-\mu^+\mu^-$	$4.17 \pm 0.12 \pm 0.40$	± 0.35	± 0.16	0	~ 10
$\pi^+K^-e^+e^-$	$4.0 \pm 0.5 \pm 0.2$	± 0.35	± 0.16	0	~ 10
$\pi^+\pi^-\mu^+\mu^-$	0.96 ± 0.12	± 0.35	± 0.16	$10^{-3} - 10^{-4}$	~ 1
$\pi^+\pi^-e^+e^-$	< 7	± 0.35	± 0.16	$10^{-3} - 10^{-4}$	~ 1
$K^+K^-\mu^+\mu^-$	0.15 ± 0.03	< 0.7	< 0.32	$\sim 10^{-4}$	~ 0.1
$K^+K^-e^+e^-$	< 11	< 0.7	< 0.32	$\sim 10^{-4}$	~ 0.1
$\pi^0\ell^+\ell^-$	< 4	< 3.7	< 1.7	1×10^{-6}	0.21
$\eta\ell^+\ell^-$	< 3	< 7.7	< 3.5	2.5×10^{-4}	0.05
$\eta'\ell^+\ell^-$	—			9.7×10^{-6}	0.02
$\bar{K}^0\ell^+\ell^-$	< 24	< 7.7	< 3.5	0	0.43

*Uncertainties scaled to 5 ab^{-1}

Conclusions

- The Belle II experiment will have a rich charm physics program
  - Direct and indirect CPV studies in charm mesons and baryons
  - Additional prospects in charm spectroscopy (the topic of another talk)

- Belle II is expected to make a wide range of forefront measurements with discovery potential
  - High statistics, good performance for neutral particles

- LOIs: RF/SNOWMASS21-RF1_RF4_BelleII-030, RF/SNOWMASS21-RF1_RF0_Bennett-021